CARBON AND OXYGEN GALACTIC ABUNDANCE GRADIENTS: A Comparative Study of Stellar Yields

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ABSTRACT

Chemical evolution models for the Galactic disk under an inside-out formation scenario are presented for seven sets of stellar yields, all dependent on metallicity. The effects of massive-star yields and low-and-intermediate-mass-star yields on the C/O chemical history of the solar neighborhood and on abundance gradients are discussed. Model predictions are compared with abundance ratios from nearby H II regions, B-stars, dwarf stars, and the Sun.

The increase of C/O with metallicity in the disk of the solar vicinity is due to massive stars sole. Models with yields by Maeder (1992) or yields by Portinari, Chiosi, & Bressan (1998) can reproduce the increase of C/O with metallicity in the solar neighborhood, while models assuming yields by Woosley & Weaver (1995) and Woosley, Langer, & Weaver (1993) can not. Models based on yields by Maeder (1992) are in agreement with the C/O gradient, while those based on yields by Woosley & Weaver (1995) and Woosley et al. (1993) or Portinari et al. (1998) are not. Model results call for: i) yields that account for metal-dependent stellar winds, and ii) a more complicated mass-loss rate law than $Z^{0.5}$ for massive stars.

C/O abundance ratios predicted with yields by Marigo, Bressan, & Chiosi (1996, 1998) are higher that those by Renzini & Voli (1981), and these last ones higher than those by van den Hoek & Groenewegen (1997).

Predicted O/H, and surface density distributions are in agreement with observations using any set of yields. The $\Delta Y/\Delta Z$ values are computed for different combinations of seven sets of stellar yields. All models agree with the $\Delta Y/\Delta Z$ value derived from M17, but are smaller than those derived from other H II regions.

Subject headings: Galaxy: abundances - Galaxy: evolution - stars: evolution

1. INTRODUCTION

In a chemical evolution model that assumes an infall of H and He gas, without mass loss by galactic winds or radial flows, the predicted C/O abundance ratio depends mainly on the stellar yields and the initial mass function. In this work the initial mass function is fixed and therefore, the C/O value is used to test the stellar yields.

A stellar yield of some element X_i is the mass fraction of a star of initial mass m converted to X_i and ejected to the interstellar medium (ISM). Obviously, stellar yields depend on assumptions of stellar evolution models. In the 80' no stellar yield sets for massive stars ($m > 8$ M$_\odot$) of different metallicities were computed. On the other hand, in this decade Maeder (1992, M92) published stellar yields for He, C, O, and Z for two initial metallicities ($Z = 0.001$ and 0.02) and for objects with initial mass in the 9-120 M$_\odot$ range. Then, Woosley & Weaver (1995, WW) calculated stellar yields for 80 elements and isotopes for models with initial masses between 11 and 40 M$_\odot$ and for five initial metallicities ($Z/Z_\odot = 0$, 10^{-4}, 0.01, 0.1, and 1), where the initial abundance ratios were not scaled to the solar abundance. Recently, Portinari, Chiosi, & Bressan (1998, PCB) published stellar yields of 17 elemental species for a wide range of metallicities ($Z = 0.0004$, 0.004, 0.008, 0.02, and 0.05) and masses (6-120 M$_\odot$).

Renzini & Voli (1981, RV), van den Hoek & Groenewegen (1997, HG), and Marigo, Bressan, & Chiosi (1996, 1998, MBC) calculated stellar yields for low and intermediate mass stars (LIMS, $0.8 < m/\mathrm{M}_\odot < 8$). Van den Hoek & Groenewegen (1997) obtained a grid of stellar yields for 5 metallicities (Z =0.001, 0.004, 0.008, 0.02, and 0.04) and the others for only two (RV for Z =0.004, and 0.02 and MBC for Z =0.008 and 0.02). The unique complete grid of stellar yields computed by the same evolutionary tracks (Padova group) is formed by PCB and MBC.

Carigi (1994) had already found that the evolution of [C/O] with [O/H] in the solar vicinity can be explained by M92 yields due to the behavior of the C and O yields in relation to the initial Z. Prantzos, Vangioni-Flam, & Chauveau (1994) concluded that the metallicity dependent yields of Maeder (1992) are able to reproduce the growth of [C/O] in the solar neighborhood. In this work the evolution of [C/O] will be extended to the Galactic disk, with the aim to study the behavior and differences of sets of yields -from massive stars and LIMS- dependent on metallicity in the chemical evolution models for the disk and the solar vicinity.

Many chemical evolution models of the solar vicinity and the Galactic disk assume M92 yields (e.g. Giovagnoli & Tosi 1995, Prantzos & Aubert 1995, Carigi 1996), WW yields (e.g. Timmes, Woosley, & Weaver 1995, Chiappini, Matteucci & Gratton 1997, Allen, Carigi, & Peimbert 1998, Prantzos & Silk 1998), or Padova yields (eg. Portinari et al. 1998, Tantalo et al. 1998). Since these sets of yields are different, I decided to build chemical evolution models to find out which set reproduces better the ISM abundances. In this work, abundances predicted by chemical evolution models for the Galactic disk using these sets of stellar yields will be compared for the four common elements among the sets (H, He, C, and O).

All chemical abundances presented in this paper are by number, with the exception of $\Delta Y/\Delta O$, and $\Delta Y/\Delta Z$, that are given by mass.

The paper has been organized as follows: The data that models should reproduce are presented in §2. In §3 the assumptions adopted in the chemical evolution models are described. In §4 the results of these models are shown and explained. The discussion and conclusions are presented in §5 and §6, respectively.

2. OBSERVATIONAL CONSTRAINTS

In this work, the compilation by Peimbert (1999) and the recent data of Esteban et al. (1998, 1999a, 1999b) are used as abundance constraints for the models. He/H, C/H, and O/H values, for the Galactic H II regions M17, M8, and Orion are taken from Peimbert's Table 1, but corrected for dust depletion, adding 0.08 dex and 0.10 dex to the O and C abundances respectively, as suggested by Esteban et al. (1998). In the modeling, I attempt to fit the abundance gradients to be within the average values by Peimbert (1999) and those obtained from the observations by Esteban et al. (1998, 1999a, 1999b) considering temperature fluctuations ($t^2 > 0.00$). Average O/H gradients computed by Peimbert (1999) are based on the gradients from Esteban et al. (1998, 1999a, 1999b), Shaver et al. (1983), and Deharveng et al. (1999). Since in the literature there are C/O values based on recombination lines only for M17, M8, and Orion, the average C/H gradients is obtained from Esteban et al. (1998, 1999a, 1999b) and Peimbert et al. (1992). The relative enrichment $\Delta Y/\Delta O$ and $\Delta Y/\Delta Z$ values for M17, M8, and Orion are taken from Peimbert (1999, $t^2 > 0.00$), which have already been corrected for dust (also as suggested by Esteban et al. 1998).

O/H abundances and gradient from B-stars are in agreement with those from H II regions (Gummersbach et al. 1998, Smartt & Rolleston 1997), but the C/H values are lower by at least 0.3 dex, and the C/H gradient is twice as flat (Gummersbach et al. 1998). The gradients from B-stars shown in Table 3 were computed using the data by Gummersbach et al. (1998) and Smartt & Rolleston (1997) for our studied galactocentric range ($4 < r < 10$ kpc). The inner B-star of each paper was eliminated due to uncertain abundances, according to the respective authors. The He/H data by Gummersbach et al. (1998) will not be considered in this paper because the dispersion is very high ($-1.1 < \log(\mathrm{He/H}) < -0.5$) corresponding to $14 < \Delta Y/\Delta O < 150$, this range does not provide a useful constraint for chemical evolution models. The difference in He abundance in B-stars may be due to contamination in the outer stellar layers by helium produced by the stars or to errors in the abundance determinations. B-stars and H II regions show different values of C/O gradients, both of these values are negative. Therefore, the fact that there is a negative C/O gradients in our Galaxy is used as an observational constraint.

The C/O history for the solar vicinity will be constrained by C/O abundances from dwarf stars located 1 kpc around the Sun (Gustafsson et al. 1999) and the solar value from Grevesse & Sauval (1998). Since C/H values from B-stars are lower than those from H II regions, two different present-day C/O values will be presented. The increase of C/O with Z in the solar vicinity is other observational constraint.

Planetary nebulae will not be used as observational constraints because C is produced by their progenitors. The models by Renzini & Voli (1981), van den Hoek & Groenewegen (1997), and Marigo et al. (1996, 1998) predict C enrichment in the envelope during the evolution of stars with masses lower than $\sim 8\ \mathrm{M}_{\odot}$. Moreover, Peimbert, Torres-Peimbert, & Luridiana (1995) and Peimbert, Luridiana, & Torres-Peimbert (1995) found C/H values higher than the solar value, by at least 0.1 dex, for the vast majority of planetary nebulae in their sample.

Another important observational constraint is gas consumption, measured as the ratio of the gas to the total surface mass densities, $\sigma_{gas}/\sigma_{tot}$. In this work the observed σ_{gas} distribution, as compiled by Matteucci & Chiappini (1999), is used together with an exponential σ_{tot} distribution with a 3 kpc scale-length and a $\sigma_{tot}(r_{\odot}) = 45\ M_{\odot}pc^{-2}$ amplitude (Kuijken & Gilmore 1991). A galactocentric distant for the Sun, $r_{\odot}$, of 8 kpc is assumed.

Summarizing, the observational constrains just described are used in this study as follows: a) All models (for all and each yield set) are build to exactly reproduce: i) the observed gas fraction distribution of the galaxy, $\sigma_{gas}/\sigma_{tot}$; ii) the observed O/H galactic gradient. b) In order to study the differences among available yields sets, the model predictions are then compared to: i) the observed rise of C/O with metallicity (or equivalently with time) in the solar neighborhood; ii) the observed decrease of the C/O abundance with galactocentric distance.

3. CHEMICAL EVOLUTION MODELING

The essence of this work is to explore models assuming different sets of stellar yields, all dependent on metallicity: i) for massive stars ($8 < m/\mathrm{M}_{\odot} < 85$): one by Maeder (1992), other by Woosley & Weaver (1995) and Woosley, Langer, & Weaver (1993) (WLW), and another by Portinari, Chiosi, & Bressan (1998); ii) for LIMS: Renzini & Voli (1981), van den Hoek & Groenewegen (1997), Marigo, Bressan, & Chiosi (1996, 1998), and Portinari et al. (1998).

All the models are built to reproduce two observational constraints: the O/H abundance gradient from H II regions and B-stars, and the σ_{gas} distribution from 4 to 10 kpc. Models are very similar to the infall model of Allen, Carigi, & Peimbert (1998), but with somewhat different assumptions:

a) The star formation rate is proportional to a power of σ_{gas} and σ_{tot}: $SFR(r,t) = \nu\ \sigma^{x}_{gas}(r,t)\ \sigma^{x-1}_{tot}(r,t)$, where ν and x are constant in time and space, and fixed such that the observational constraints are reached at 13 Gyr, the age of the model.

b) Three sets of metal-dependent stellar yields from massive stars are used: i) Geneva yields: M92 for $9 \leq m/\mathrm{M}_{\odot} \leq 85$ (high mass-loss rate); ii) Santa Cruz yields: WW for $11 \leq m/\mathrm{M}_{\odot} \leq 40$ (models "B" for 30, 35 and 40 $\mathrm{M}_{\odot}$), and WLW for $m = 60\ \mathrm{M}_{\odot}$ and $m = 85\ \mathrm{M}_{\odot}$; iii) PCB yields: Portinari et al. (1998) for $9 \leq m/\mathrm{M}_{\odot} \leq 85$. Since $Z_{max} = Z_{\odot}$ for the Geneva and Santa Cruz groups, then yields ($Z > Z_{\odot}$) = yields($Z_{\odot}$). In all cases, effects due to black hole formation are not considered.

c) Three sets of metal-dependent stellar yields for LIMS are used: i) RV yields: Renzini & Voli (1981) for $1 \leq m/\mathrm{M}_{\odot} \leq 3$ ($\alpha = 0.0$,$\eta = 0.3$, case A), for $3 \leq m/\mathrm{M}_{\odot} \leq 8$ ($\alpha = 1.5$,$\eta = 0.3$, case A). ii) HG yields: van den Hoek & Groenewegen (1997) for $0.8 \leq m/\mathrm{M}_{\odot} \leq 8$ ($\eta_{AGB} = 0.4$,$M_{HBB} = 0.8$). iii) MBCP yields: Marigo et al. (1996) for $0.8 \leq m/\mathrm{M}_{\odot} \leq 3$; Marigo et al. (1998) for 4, 4.5, and 5 $\mathrm{M}_{\odot}$; Portinari et al. (1998) for 6 and 7 $\mathrm{M}_{\odot}$.

d) The fraction of binary systems predecessors of SNIa is taken as $A = 0.07$. Contrary to Carigi (1994), SNIb produced by binary systems have not been considered.

Input parameters for the set of models are summarized in Table 1. Column (2) lists x, the SFR power of σ_{gas}, and column (3) the efficiency factor, ν, of each model. The slope of the final abundance gradients is basically governed by x; while ν and x together determine the O abundance. Models are divided in three big groups (column 4), assuming M92, WW&WLW, or PCB yields. M92 and WW&WLW yields have been complemented with RV, HG, and MBCP yields. Three subgroups of models have been computed according to the type of interpolation used (Z^n, n =0.5, 1, or 2) between the two metallicities considered by Maeder (1992). This table shows just one model for the PCB yields (C-model), because the Padova yields (PCB+MBCP) form a complete and consistent set.

Since LIMS do not produce O, each set of yields from massive stars requires different values of x and ν to match the same observational constraints. Since the M92-O yields for $m > 25$ M$_\odot$ decrease with metallicity, O gradients saturate quicker calling for higher x values. On the other hand, WW-O yields are almost independent of metallicity, and WLW-O yields are lower (at most by a factor of 10) than M92-O yields at low metallicity, forcing higher ν values for the WW&WLW modeling to reach the observed O/H of H II regions. Since PCB-O yields are lower than M92-yields at low Z, it is required that $\nu_{\rm C-model} \sim \nu_{\rm M-models}$ when the interpolation is weighted to high metallicities.

Since the yields for supermetallic stars are similar than those by WW, then $x_{\rm C-model} \sim \nu_{\rm W-models}$

Infall models of this kind produce abundance gradients that flatten out with time (Carigi 1996), so the M-models require higher x exponents to reproduce the O/H gradient (at a fixed age of 13 Gyr).

4. MODEL RESULTS

First of all, I will show in the Figure 1 the C/O evolution in the solar vicinity predicted by models that consider yields by Maeder (1992). How the yields for massive stars vary with Z is not well known: the behavior of the PCB yields with Z is not simple and the Santa Cruz yields are almost independent of Z. Therefore, the influence on the C/O ratio due to the interpolation type assumed in the M92 yields has been explored in Figure 1a. From this figure one can notice that the rise of C/O with time is smaller with n (Z^n) between 1.5 and 9 Gyr, out of this lapse the increase is almost the same. For this reason, it is important to compute yields for intermediate metallicities. On the other hand, since LIMS produce carbon, the influence of these stars over the C/O abundance has been studied in Figure 1b. One can see that RV predict less carbon production than MBC but more than HG for $t > 1$ Gyr. The best models using combinations of different interpolations in Maeder's yields with LIMS yields (M-models = MRV1, MHG1, MMBC2) are shown in Figure 2.

Figures 2(h),3(h), and 4(h) present the predicted C/O chemical enrichment history for the solar neighborhood, when Geneva, Santa Cruz, and Padova yields are assumed, respectively. Moreover, the following observational data are shown i) the observed abundance in the Sun and in the neighboring disk dwarf stars, ii) a C/O value at $r_{\odot}$ derived from the observed gradient for H II regions, and iii) a C/O average value for the nearest B-stars from Gummersbach et al. (1998). From these figures, one can see that the C/O abundance always increases with time in the M-models and the C-model, in agreement with most of the observations (dwarf stars, Sun, and H II regions). Furthermore, the results of the W-models do not show a recent rise of C/O, in disagreement with observations.

This is because the M92 and PCB-O yields increase with mass and decrease with metallicity, while the C yields increase with both, mass and metallicity for $Z \leq Z_{\odot}$. At the onset of the evolution, the WLW yields from very massive stars ($m > 40$ M$_{\odot}$) enrich the ISM with ever more oxygen through O-yields that increase with mass. Once these stars die, after a few million years, the C/O of the W-models behaves like in the M-models because, for $m < 40$ M$_{\odot}$, both sets of yields are similar at low metallicities. Since the WW yields do not depend on metallicity, the W-models reach (at ~ 3.5 Gyr) a plateau in C/O that decreases slowly with time.

The C-model predicts two plateaus, the first one at ~ 5 Gyr and the other for $t >$11 Gyr. The second one is due to the contribution of supermetallic stars. These stars have extreme winds which occur before C and O are synthesized, so the winds are He rich, while C and O are produced during the SN explosion. Therefore, the behavior of the yields for these stars is similar to that predicted by WW.

Table 2 summarizes the present-day predictions for the solar neighborhood from all models. M-models reproduce the observed C/H and C/O values from H II regions. WRV and WHG models predict C/H and C/O values in agreement with B-stars, while the WMBC model results agree with C/H and C/O from H II regions.

From Figure 1, for instance, and Table 2, it can be noted that the C/O average for B-stars is lower than for H II regions and for dwarf stars, mainly due to the low C/H values observed in these B-stars.

Predictions for the Galactic disk are summarized in Figures 2-4 (a-g) and Table 3. From the figures and the table it can be seen that:

a) The C/H gradients predicted by the best models with M92 yields are similar to the observed ones from H II regions. The gradients from the W-models (considering WW&WLW yields) or the C-model are flatter by about 0.04 dex kpc^{-1} and are more similar to the observed ones from B-stars;

b) C/H abundance ratios from the M, WMBC, and C models agree with the H II regions observations, but those from WRV and WHG models are lower by at least 0.1 dex and are in agreement with C/H from B-stars;

c) M-models are the sole models that reproduces the high C/H and C/O values of M17;

d) The negative C/O gradients predicted by the M-models are in very good agreement with the observations. The positive gradients predicted by W-models or C-model are in contradiction with the observations;

e) The C/O values from W-models agree with those determined from B-stars, while the C/O values from M and C models agree with the C/O values determined from H II regions;

f) M-models and the WMBC-model reproduce the observed He/H abundances in H II regions, with the former yielding the best agreement;

g) RV yields predict lower C and He than MBC and higher than HG;

h) M-models predict strong negative $\Delta Y/\Delta O$ gradients while W-models and C-model yield almost no gradient;

i) Predicted $\Delta Y/\Delta Z$ gradients are almost flat for every model;

j) All models, with the exception of the WMBC model, predict helium to heavy elements abundance ratios ($1.6 < \Delta Y/\Delta Z < 1.0$) lower than observed in M8 and Orion.

The C/O gradients from the W-models and the C-model are almost flat because WW yields are almost independent of Z and the very-metal-rich stars eject C and O in SN explosions and not in winds, both facts imply a saturation in C/O.

The He/H gradients predicted by the M-models are steeper than that obtained by the C-model because the very-massive and super-metallic stars eject a smaller amount of He than solar metallicity stars (PCB)

I present in Figure 5 the predicted evolutions of C/O versus O/H for the solar neighborhood. In addition to Galactic data, C/O and O/H values for extragalactic H II regions are shown. Objects in the halo and in the disk of the solar neighborhood (cylinder of radio 1 kpc centered in the Sun), and in external galaxies call for an increase of C/O with O/H enrichment. The models that reproduce this increase have been shown in this figure, therefore no W-model is presented. The agreement for log(O/H) < -3.8 is not so good, with the exception MHG1. Again, here we can see that C yields for intermediate mass stars given by HG are lower than those obtained by RV o MBCP. It is important to note that I have assumed a linear interpolation with metallicity for the RV and MBCP yields, based on the Z-behavior of the HG yields.

A powerful tool to compare chemical evolution models with interstellar medium abundances is given by the relation

$$\log(\mathrm{C/O}) = a \log(\mathrm{O/H}) + b. \tag{1}$$

In Table 4 I present the a values predicted by the models, considering different concentric galactic rings: i) a very local disk, between $r = 6$ and $r = 8$ kpc, and ii) the complete area studied in this paper. Moreover, in this table I show the a values derived from four sets of observations, two galactic ones and two extragalactic ones; for the B-stars result it is assumed that the C and O abundances correspond to those of the interstellar medium. The observed a values indicate that the negative C/O local gradient may be extended to the whole Galactic disk. As can seen from the table the observed a values are in good agreement with the M-models and in disagreement with the W-models and the C-model, reiterating the results presented in Figure 5. According to the discussion of Figure 5 the best models are: MRV1, MHG1, and MMBC2.

5. DISCUSSION

The determinations of C/O from H II regions in spiral and irregular galaxies (Garnett et al. 1999), H II regions in our Galaxy (Peimbert, Torres-Peimbert & Ruiz 1992, Esteban et al. 1998, 1999a, 1999b), and dwarf stars in the solar vicinity (Gustafsson et al. 1999); all converge to the fact that C/O must increase with metallicity. M92 yields can explain this behavior, Padova yields can partially, while WW&WLW yields can not. Other authors (Ferrini, Matteucci, Prantzos, Timmes, and Tosi, see Tosi 1996 for references) using different chemical evolution models, have predicted flat C/O gradients (Tosi 1996) because all of them have considered WW yields, which are almost independent of Z, or yields at a fixed Z.

Carigi (1994) and Prantzos et al. (1994) had already concluded that the evolution of [C/O] with [O/H] or [Fe/H], respectively, in the solar vicinity can be explained by the metal dependent yields of Maeder (1992). I have extended these previous works to the Galactic disk using the recent C determinations in H II regions and B-stars as observational constraints. Moreover, I have considered seven sets of yields, all of them formed by the only stellar yields dependent on the initial stellar metallicity that one can find in the literature.

A main difference between these sets of yields resides on the stellar-wind assumptions. WW do not consider stellar winds at any stage, and M92 and PCB assume a mass-loss rate proportional to $Z^{0.5}$ and $m^{2.5}$ during the post-main-sequence phases.

C and O yields from M92, PCB, and WW are similar for $m < 25$ M$_\odot$, where stellar winds are not so relevant. In M92 and PCB, most of the net C is produced before the SN stage, and since the wind strength increases with metallicity, the C yield increases with Z. On the other hand, O is mainly ejected during the SN stage and, since the amount of O expelled by the SN depends on the stellar mass just before the SN explosion, the M92 and PCB-O yield decreases with Z. This fact causes the M-models and the C-model to reproduce the rise of the C/O in the solar vicinity.

The increase of C yields and the decrease of O yields with Z can not be extrapolated to $Z > Z_\odot$. According to PCB, the C to O yields ratio decreases from $Z = Z_\odot$ to $Z = 2.5Z_\odot$. The supermetallic and massive stars have early and intense winds, which occur before the stars synthesize C and O. Therefore, their C and O yields are similar to those of metal-poor stars, that mainly eject C and O in the SN explosion. This behavior of the C and O yields produce a saturation of the C/O abundance ratio at $\sim$ -0.1 dex, which produces flatter gradients for the C-model. Since in M-models I have assumed that the supermetallic stars behave like metal-solar stars, the C-model would predict a negative C/O gradient if the mass-loss rate for $Z = 2.5Z_\odot$ is similar to, at least, that for $Z = Z_\odot$

It is important to note that in the W-models I did not include the wind contribution to the C and O yields because WLW only present information to calculate He expelled by winds. If winds were considered in these models, the C yield would certainly be higher but, given the low weight at the high-mass end of the initial mass function, hardly enough to reproduce the present-day C/O abundances. When the WLW yields are not taken into account (by reducing the upper mass-limit to 40 M$_\odot$) the predicted C/O decreases at times earlier than 0.4 Gyr, but still remains low and basically constant for the rest of the evolution (Carigi & Peimbert 2000).

The M-models and C-model agree better with the younger objects in the solar vicinity than with the older. The agreement would improve if metal-poor stars eject more oxygen and less carbon than $Z^{0.5}$. The M-models are in in agreement with data for spiral and irregular galaxies while the W-models are not, as Garnett et al. (1999) have discussed. Then again, the general agreement would be even better if the C and O yields for metal-poor stars were more dependent on metallicity than assumed by M92 and PCB. Furthermore, the C/O value of I Zw 18 determined by Garnett et al. (1995, C/O= -0.60 ± 0.10 dex) would be hard to explain (not so the lower value of Izotov & Thuan 1999, $< \log(\mathrm{C/O}) >= -0.78 \pm 0.03 >$). It should be noted that the models presented in Figure 5 were made to reproduce the Galactic disk and therefore, the comparison of the extragalactic H II regions and halo objects is only indicative. Specific models for each galaxy or for the Galactic halo should be carried out, see for example the models by Carigi, Colín, & Peimbert (1999) and Carigi & Peimbert (2000).

Moreover, the M-models and the C-model agree well with the [C/H], [C/O], and [C/Fe] vs [Fe/H] relations observed by Gustafsson et al. (1999) in dwarf stars of the solar vicinity, after correcting for the adopted solar abundances (Grevesse & Sauval 1998 as opposed to Anders & Grevesse 1989). The predicted relations are matched at high [Fe/H] and become slightly lower-than observed at lower metallicities; again, a behavior that calls for more metal dependency of the C and O yields for metal-poor stars than $Z^{0.5}$. W-models match basically the relation slopes, but again predict a lower C abundance than observed (by $\sim$ 0.3 dex in C/H and $\sim$ 0.2 dex in C/Fe).

Maeder (1993), Woosley & Weaver (1995) and Portinari et al. (1998) have assumed different values for the $C^{12}(\alpha,\gamma)O^{16}$ reaction rate. It is known that this rate is uncertain by about a factor of 2. This uncertainty causes minor differences in the behavior of C/O as a function of metallicity predicted by the models, but more severely affects the absolute C/O value. This change in the absolute C/O value does not alter the conclusions of this paper. In other words, to a very good approximation, a change in the $C^{12}(\alpha,\gamma)O^{16}$ rate modifies b in equation (1), but not a.

The C/H values derived from Galactic B-stars are about 0.3 dex lower than those from Galactic H II regions and from disk dwarf stars of the solar vicinity. Carbon abundances of B-stars are not easy to understand and may not be representative of the present-day C in the ISM, because: i) B-stars being so young (10^{-3} - 10^{-2} Gyr) they would be expected to be richer in C than most dwarf stars, but the observed C/H in B-stars in the solar vicinity is very similar to the C of the poorest dwarfs. ii) The O and N abundances and gradients from B-stars and from H II regions are very similar (surprisingly so for N), so it is difficult to understand why the C/O gradient from B-stars is almost flat, while the one from H II regions is not. iii) A real C/O gradient is supported by the fact that other two nearby spiral galaxies, M101 and NGC 2403, also show significant C/O gradients, -0.04 and -0.05 dex/kpc respectively (Garnett et al. 1999). iv) C/O from H II regions, the Sun, and dwarf stars are consistent with each other, but not with the C/O from B-stars in the solar vicinity.

It is known that intermediate mass stars ($m < 8$ M$_\odot$) produce carbon and not oxygen. Carigi (1994) found that yields by Renzini & Voli (1981) can not explain the C/O increase with the metallicity in the solar neighborhood. Prantzos et al. (1994) suggested that C-yields higher that those predicted by Renzini & Voli could reproduce the observed rise in C/O. The other two sets of yields for LIMS dependent on Z that exist in the literature (van den Hoek & Groenewegen 1997, and Marigo et al. 1996, 1998) can not explain the recent rise of C/O in the solar vicinity. However, LIMS have an important role in the early evolution of C/O.

6. CONCLUSIONS

Based on basic chemical evolutionary models for the Galactic disk, assuming different sets of stellar yields dependent on metallicity, I reach the following conclusions:

a) Different sets of stellar yields predict different C/O values. The recent rise of C/O with O/H is due mainly to massive stars. The early rise of C/O with O/H is due to massive stars and LIMS.

b) Models using stellar yields with stellar winds dependent on Z (Maeder 1992, Portinari et al. 1998) reproduce the rise of C/O with time shown by H II regions, the Sun, and dwarf stars within the solar vicinity.

c) Models considering Maeder's yields are also successful in reproducing the C/O Galactic abundances and gradient determined from H II regions.

d) The model assuming Padova yields reproduces C/O abundances but not C/O Galactic gradients from H II regions, because stellar winds $\propto Z^{0.5}$ are too strong for supermetallic stars.

e) Models assuming yields from WW&WLW reproduce only the C/O abundances from B-stars, but fail to reproduce the other observational constraints.

f) Since the C/H abundances in B-stars are lower than in disk dwarf stars of different ages in the solar neighborhood, while the O/H value is very similar, the C/O value from these B-stars may not be as good observational constraint.

g) The main difference between the sets of yields of massive stars arises because Geneva and Padova groups consider stellar winds dependent on metallicity while WW do not and WLW only partially. I then conclude that Z-dependent stellar winds have been important in the chemical enrichment history of the Galaxy.

h) Observations within the solar neighborhood, the Galactic disk, as well as in spiral and irregular galaxies, imply that C/O must increase with metallicity. Modeling including not only winds, but metal-dependent winds, is necessary to properly follow the chemical evolution of galaxies.

i) To improve the agreement with the C/O Galactic abundances and the C/O evolution with metallicity, the present models call for a more complicated mass-loss rate law than $Z^{0.5}$, assumed by Maeder (1992) and by Portinari et al. (1998): $\dot{M}_{wind} \propto Z^n$, such that $n > 0.5$ if $Z \ll Z_\odot$, $n \sim 0.5$ if $Z \leq Z_\odot$ and $0.5 < n < 0.7$ if $Z > Z_\odot$.

j) Models based on yields by Renzini & Voli (1981) predict less C and He than those by Marigo et al. (1996, 1998) and more than those by van den Hoek & Groenewegen (1997)

k) The $\Delta Y/\Delta Z$ value decreases in the direction MBCP - RV - HG. At the same time, it increases in the direction PCB - M92 - WW&WLW.

l) The number of H II regions with known C abundance is low, and the C/O gradient from H II regions might change with future C determinations in more H II regions. It is important to obtain C abundances from H II regions located at other galactocentric distances to determine the Galactic C/O gradient with higher accuracy.

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Fig. 1.— The C/O evolution of the solar vicinity. The predictions of the models are presented as follows: (a) Considering three different interpolations ($Z^{0.5}$, Z^1, and Z^2) of the massive-stars yields by Maeder (1992) and LIMS yields by Renzini & Voli (1981). *Long-dash-dot lines:* MRV0-model, *continuous lines:* MRV1-model, *short-dash-dot lines:* MRV2-model. (b) Assuming the Z^1 interpolation for yields by Maeder (1992) and three set of LIMS yields by: Marigo et al. (1996, 1998), Renzini & Voli (1981), or van den Hoek & Groenewegen (1997). *Long-dash lines:* MMBC1-model, *continuous lines:* MRV1-model, *short-dash lines:* MHG1-model. Observational data are as follows: *filled circle:* computed value at $r = r_\odot$ from radial gradients by Peimbert (1999); *filled triangle:* average value for the five B-stars at $r = r_\odot + 0.4$ kpc from data by Gummersbach et al. (1998); *filled squares:* dwarf stars at $r = r_\odot \pm 1$ kpc from Gustafsson et al. (1999); $\odot$: solar value from Grevesse & Sauval (1998). The ages of the dwarf stars were scaled to the age of the models.

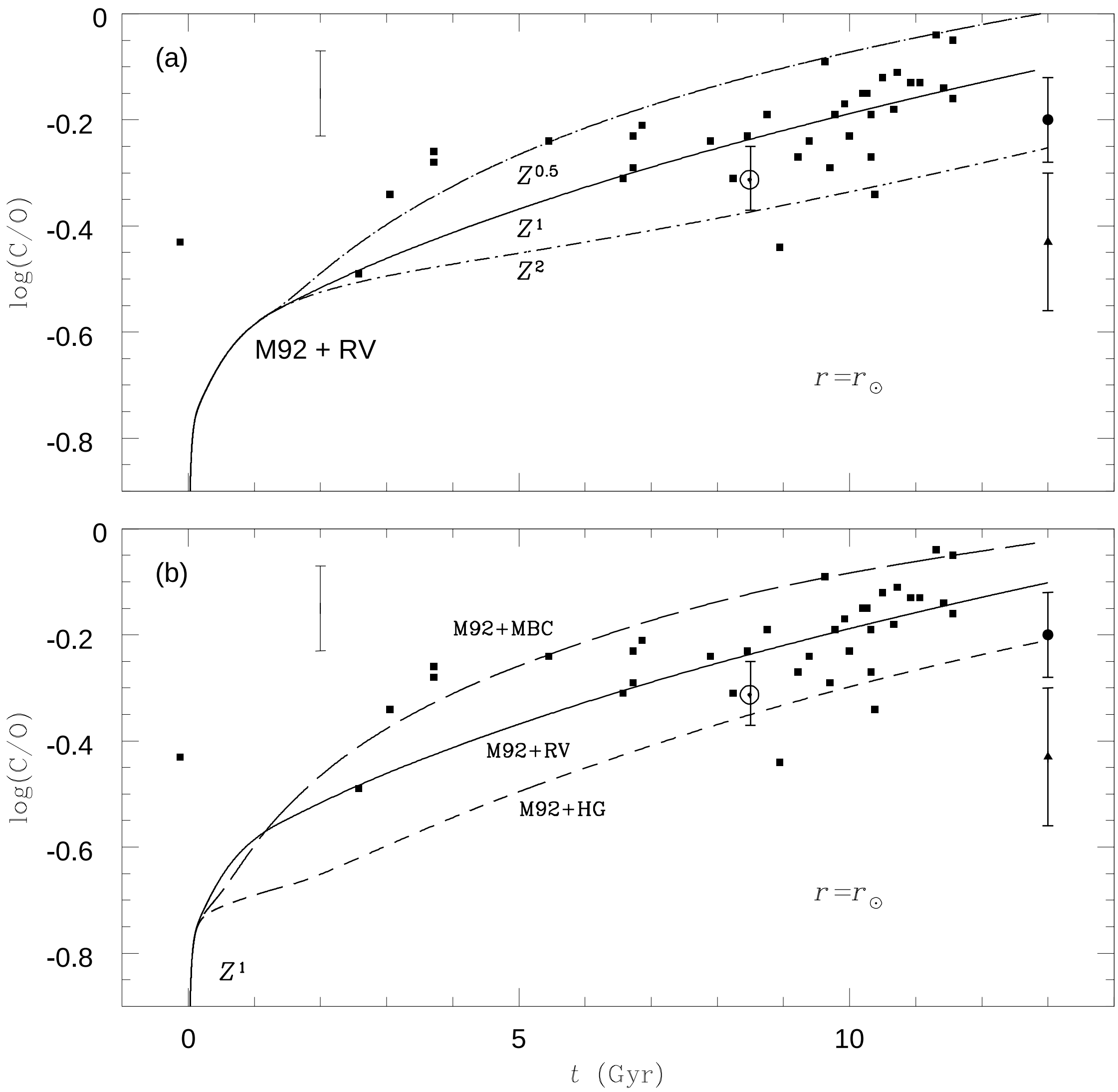
Fig. 2.— (a) Present-day radial distribution of gas surface mass density, the area enclosed by dotted lines indicates the data collected by Matteucci & Chiappini (1999); (b)-(g) observed abundance ratios and computed abundance ratios (this paper). Predictions from the best models considering yields by Maeder (1992): *long-dashed lines:* MMBC2-model, *continuous lines:* MRV1-model, *short-dash lines:* MHG1-model. Observational data: *filled circles:* gas and dust in H II regions from Peimbert (1999) and Esteban et al. (1998), respectively; *filled triangles:* B-stars from Gummersbach et al. (1998); and *crosses:* B-stars from Smartt & Rolleston (1997). The observed values correspond to M17, M8, and Orion at adopted galactocentric distances of 5.9, 6.5, and 8.4 kpc, respectively. Error bars in the left and the right represent the typical errors from data by Gummersbach et al. (1998) and Smartt & Rolleston (1997), respectively. (h) The C/O evolution of the solar vicinity, observational data as in Fig 1.

Fig. 3.— Same as previous figure. Predictions from models assuming yields by Woosley & Weaver (1995) and Woosley et al. (1993) for massive stars and Marigo et al. (1996, 1998), Renzini & Voli (1981), or van den Hoek & Groenewegen (1997) for low and intermediate mass stars. *Long-dash lines:* WMBC-model, *long-short-dash lines:* WRV-model, *short-dash lines:* WHG-model.

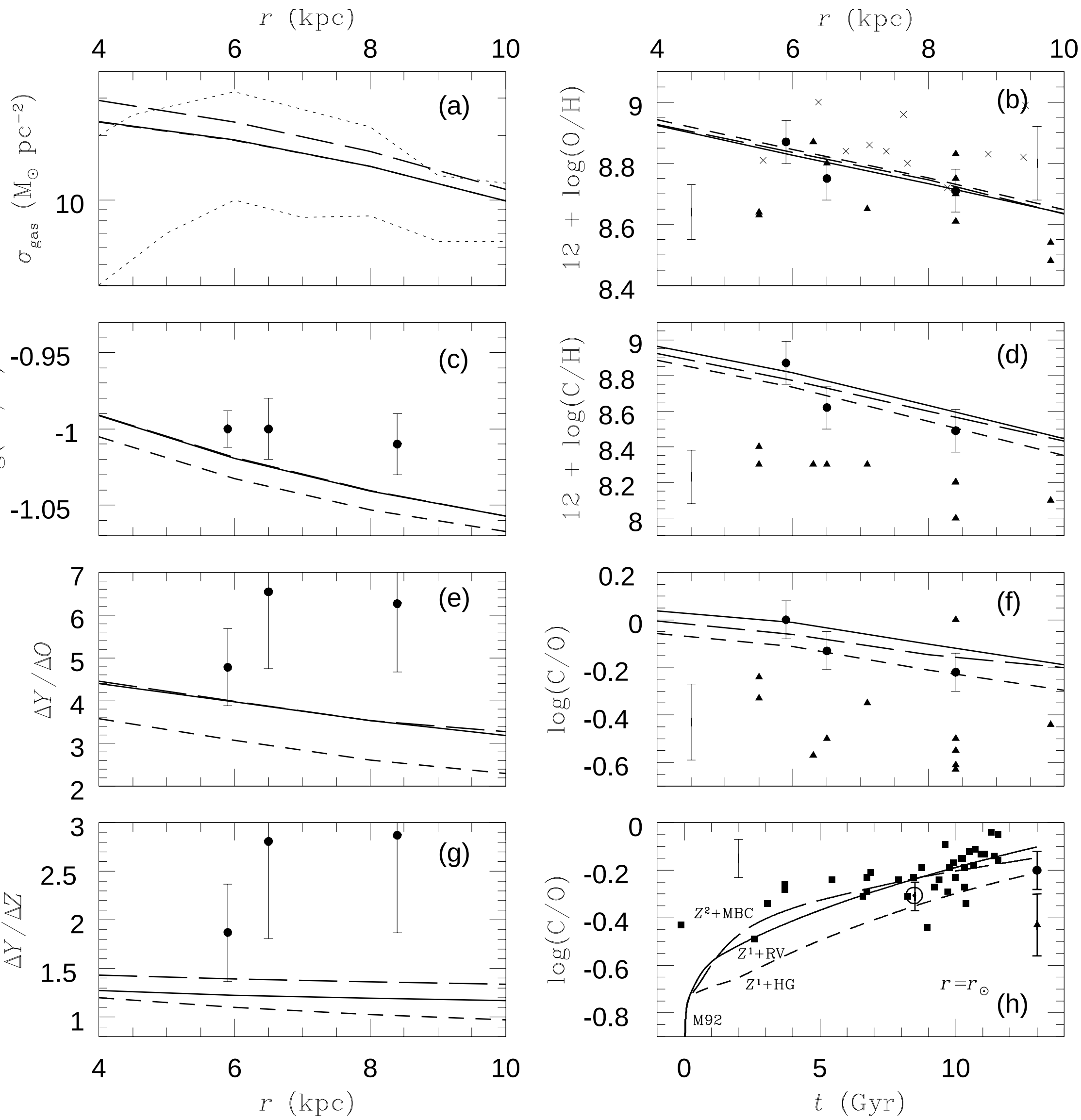
Fig. 4.— Predictions from models assuming yields by Marigo et al. (1996, 1998) for low and intermediate mass stars in combination with yields for massive stars by and Woosley & Weaver (1995) and Woosley et al. (1993), Portinari et al. (1998), or Maeder (1992). *Short-dash lines:* WMBC-model, *continuous lines:* C-model, *long-dash lines:* MMBC2-model.

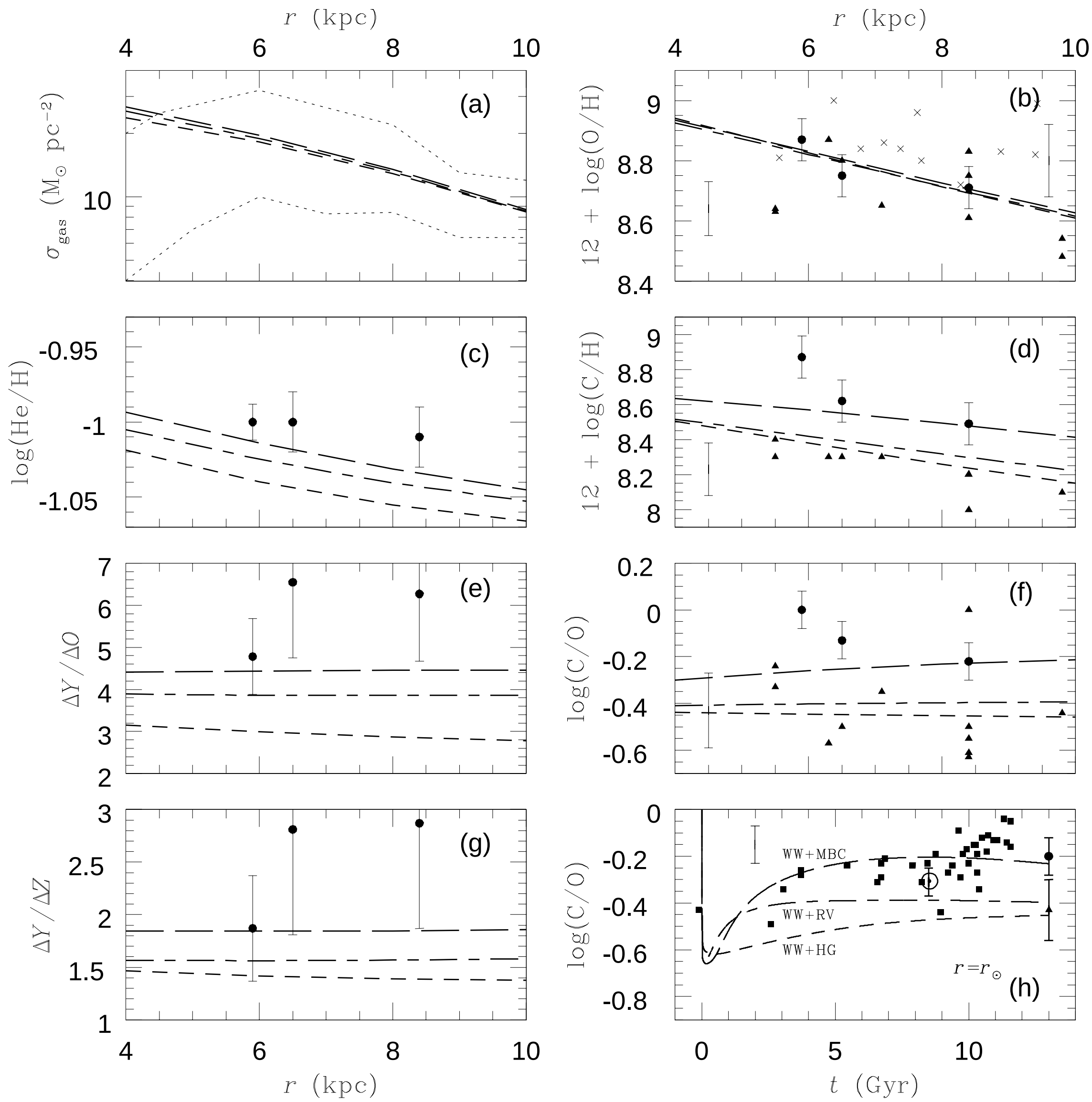
Fig. 5.— Log(C/O) versus log(O/H) relation for $r = r_\odot$. The predictions of selected models (those that reproduce this relation) are presented as follows: *dotted line:* C-model, *long-dashed line:* MMBC2-model, *continuous line:* MRV1-model, *short-dash line:* MHG1-model. Observational data for the solar vicinity (*filled symbols*) are as follows: *circle*: Orion from Peimbert (1999); *hexagons*: field halo dwarfs from Tomkin et al. (1992); *squares*: dwarf stars from Gustafsson et al. (1999), as in Fig 2; *triangle*: average B-star computed by the data by Gummersbach et al. (1998), as in Fig. 2; $\odot$: solar value from Grevesse & Sauval (1998). Error bars on the upper-left and the lower-right corners represent the typical errors from data by Gustafsson et al. (1999) and Tomkin et al.

(1992), respectively. Log (O/H) for halo dwarfs is the average of [O/H] values showed by Tomkin et al. (1992). Observational data for external galaxies (*open symbols*) are as follows: *circles*: I Zw 18NW and I Zw 18SE, values adopted from Figure 4 by Garnett et al. (1999); *hexagons*: I Zw 18NW and I Zw 18SE, abundance ratios taken from Table 5 by Izotov & Thuan (1999); abundance data for spiral galaxies (*squares*) and dwarf irregular galaxies and Magellanic Clouds (*triangles*) are obtained from Garnett et al. (1999). Plotted C/O values for spiral galaxies are the average of the abundance ratios for two different reddening laws.

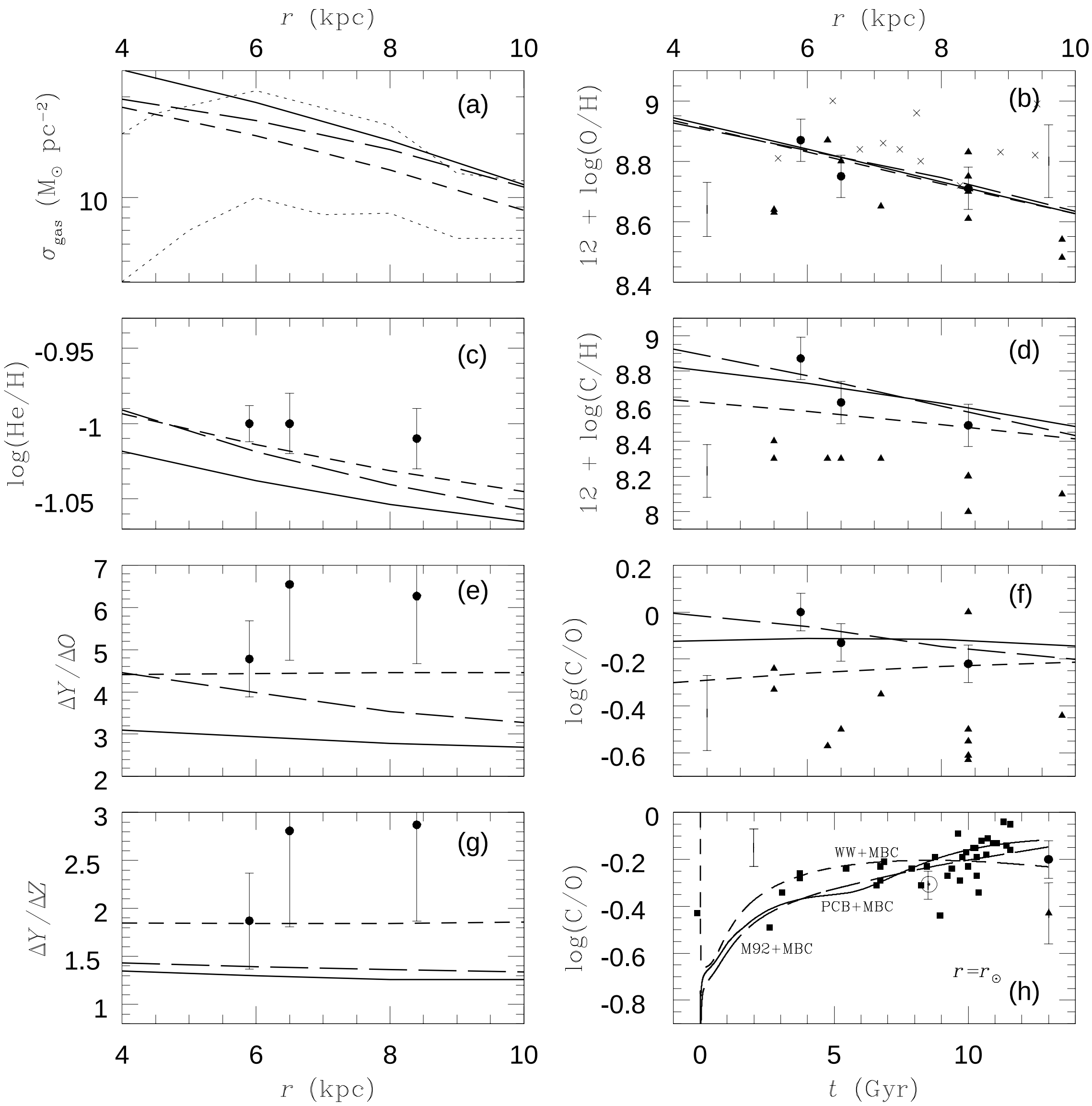


(a)
(b)
log(C/O)
0
-0.2
-0.4
-0.6
-0.8
$Z^{0.5}$
Z^{1}
Z^{2}
M92 + RV
$r = r_\odot$
M92+MBC
M92+RV
M92+HG
Z^{1}
0
5
10
t (Gyr)

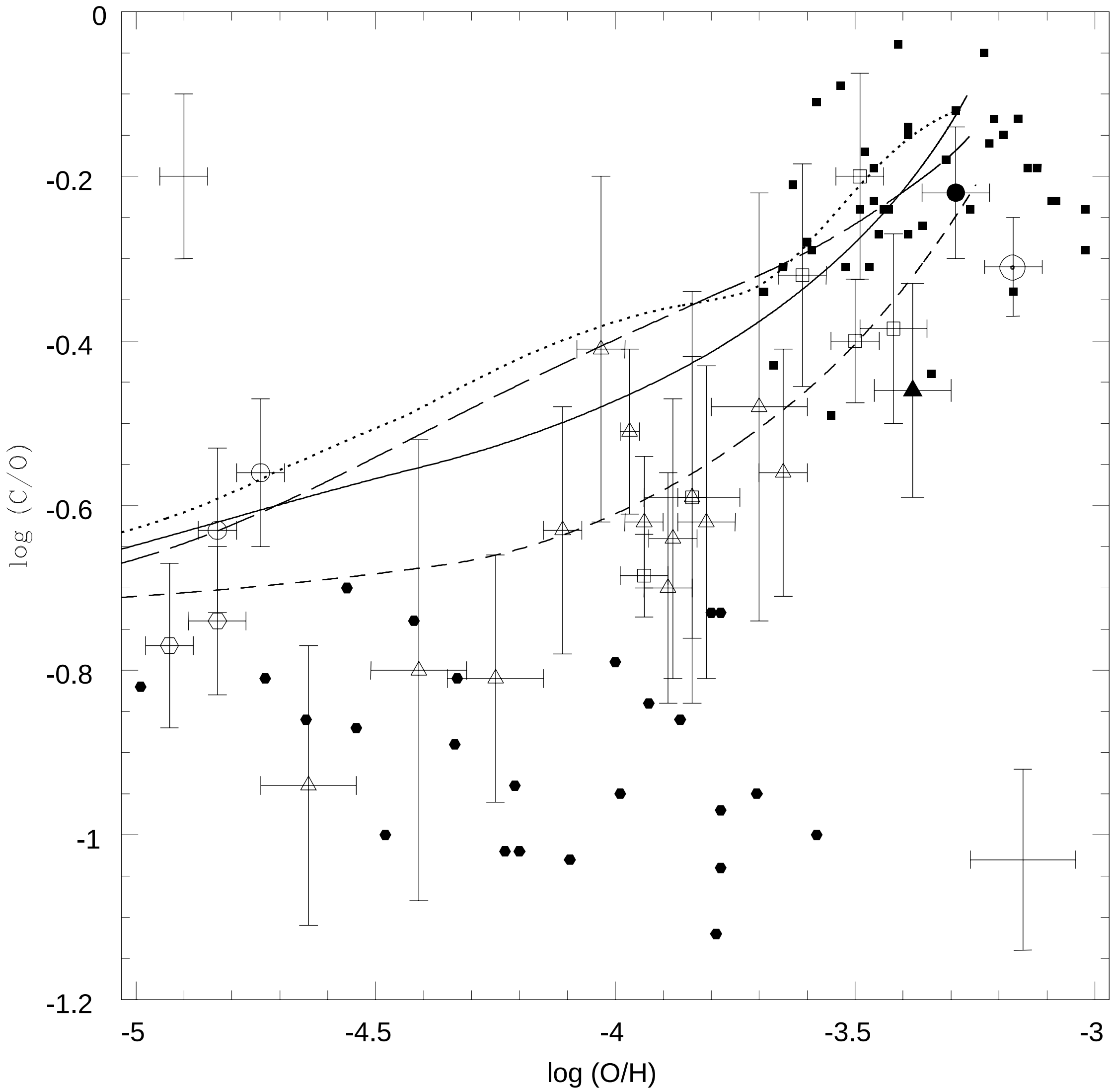

r (kpc)
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
σgas (M⊙ pc⁻²)
12 + log(O/H)
log(He/H)
12 + log(C/H)
ΔY/ΔO
log(C/O)
ΔY/ΔZ
t (Gyr)
Z²+MBC
Z¹+RV
Z¹+HG
M92
r=r⊙



r (kpc)
σ_{gas} ($M_\odot$ pc^{-2})
(a)
12 + log(O/H)
(b)
log(He/H)
(c)
12 + log(C/H)
(d)
$\Delta Y/\Delta O$
(e)
log(C/O)
(f)
$\Delta Y/\Delta Z$
(g)
WW+MBC
WW+RV
WW+HG
$r=r_\odot$
(h)
t (Gyr)



r (kpc)
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
WW+MBC
PCB+MBC
M92+MBC
r =r⊙
t (Gyr)



0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
log (C/O)
-5
-4.5
-4
-3.5
-3
log (O/H)

Table 1. Input Parameters of the Models

Model	x [a]	ν (Gyr^{-1} ($M_\odot$ pc^{-2})$^{2(1-x)}$)[a]	Massive Stars + LIMS Yields [b]	n [c]
MX0	1.22	0.048	M92 + X	0.5
MX1	1.22	0.040	M92 + X	1.0
MX2	1.22	0.033	M92 + X	2.0
WX	1.13	0.075	WW&WLW + X	
C	1.15	0.045	PCB + MBC	

[a] $SFR = \nu\ \sigma_{gas}^{x}\ \sigma_{tot}^{x-1}$

[b] X = RV, HG, MBCP

[c] Interpolation type (Z^n)

Table 2. Current Predicted and Observed Abundance Ratios for the Solar Vicinity

Model	12 + log(C/H)	12+log(O/H)	log(C/O)
MRV0	8.74	8.74	+0.00
MRV1	8.63	8.73	-0.10
MRV2	8.48	8.74	-0.25
MHG0	8.66	8.75	-0.10
MHG1	8.54	8.75	-0.21
MHG2	8.38	8.75	-0.37
MMBC0	8.81	8.75	+0.06
MMBC1	8.72	8.74	-0.02
MMBC2	8.60	8.75	-0.15
WRV	8.32	8.71	-0.39
WHG	8.26	8.71	-0.45
WMBC	8.49	8.73	-0.23
C	8.62	8.73	-0.12
Obs. M17, M8, Orion [a]	8.54 ± 0.12	8.74 ± 0.07	-0.20 ± 0.08
Obs. H II regions Average [a]	8.53 ± 0.12	8.74 ± 0.07	-0.21 ± 0.08
Obs. B-stars [b]	8.16 ± 0.12	8.62 ± 0.08	-0.46 ± 0.13
Obs. B-stars [c]	...	8.84 ± 0.10	...

[a] Computed from data by Peimbert (1999) at $r_\odot$

[b] Average values for the five B-stars at $r = r_\odot + 0.4$ kpc from data by Gummersbach et al. (1998)

[c] Average values at $r = r_\odot \pm 1$ kpc from data by Smartt & Rolleston (1997)

Table 3. Predicted [a]and Observed Present-day Radial Gradients [b]

Model	C/H	O/H	C/O
MRV0	-0.078	-0.049	-0.029
MRV1	-0.091	-0.046	-0.045
MRV2	-0.108	-0.045	-0.063
MHG0	-0.082	-0.049	-0.033
MHG1	-0.096	-0.047	-0.049
MHG2	-0.112	-0.049	-0.063
MMBC0	-0.065	-0.049	-0.015
MMBC1	-0.074	-0.046	-0.028
MMBC2	-0.087	-0.045	-0.042
WRV	-0.051	-0.053	+0.002
WHG	-0.061	-0.057	-0.004
WMBC	-0.038	-0.053	+0.014
C	-0.056	-0.054	-0.002
Obs. H II regions Average [c]	-0.106	-0.055	-0.051
Obs. B-stars [d]	-0.059	-0.038	-0.026
Obs. B-stars [e]	...	-0.017	...

[a] Between 6 and 8 kpc

[b] in dex kpc^{-1}

[c] Peimbert (1999)

[d] Computed from data by Gummersbach et al. (1998) ($r_\odot - 2.5$ kpc $\leq r \leq r_\odot + 1.8$ kpc)

[e] Computed from data by Smartt & Rolleston (1997) ($r_\odot - 2.5$ kpc $\leq r \leq r_\odot + 1.9$ kpc)

Table 4. Present-day Rise across the Galactic Disk of C/O with O/H [a]

Model	Predictions $a_{\Delta r=2}$	$a_{\Delta r=6}$
MRV0	0.58	0.56
MRV1	0.98	0.79
MRV2	1.41	1.03
MHG0	0.67	0.56
MHG1	1.04	0.81
MHG2	1.27	1.01
MMBC0	0.31	0.31
MMBC1	0.61	0.50
MMBC2	0.94	0.67
WRV	-0.05	-0.05
WHG	0.07	0.07
WMBC	-0.27	-0.28
C	0.04	0.06

Object	Δr (kpc)	Observations $a_{\Delta r}$
H II regions Average [b]	2.5	0.93
B-stars [c]	4.3	0.68
NGC 2403 [d]	5.3	0.50
M101 [d]	15.1	0.98

[a] The table presents a values derived from $\log(\mathrm{C/O}) = a \log(\mathrm{O/H}) + b$, and Δr is in kpc

[b] Computed from data by Peimbert (1999)

[c] Computed from data by Gummersbach et al. (1998)

[d] Computed from data by Garnett et al. (1999)